Preliminary studies toward Trigger-Level Analysis with Photons in ATLAS

Bachelor thesis

Leo Östman

Supervisor
Caterina Doglioni

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Department of Physics

Division of Particle Physics

Lund University

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Abstract

The Trigger-Level Analysis is a strategy for data analysis that enables recording larger amounts of events at the ATLAS experiment than the typical method of reconstructing events offline. This is done by only recording partial information about the event, and using that for analysis. As more events are analysed with this method it can be used to put lower energy constraints on the events that are analysed, meaning that events which would otherwise not pass trigger cuts can be stored.

This work considers a model of dark matter in which dark matter can interact with ordinary matter through a mediator particle. The mediator is of a mass range where it decays into two jets that are unlikely to have enough energy to pass the trigger cuts at a significant rate. A Trigger-Level Analysis could potentially probe this region of mediator masses. The work gives a preliminary look into the possibility of using photons for this, in association with dijet events. This shows that photons could potentially be used, as they display a similar performance to jets even without calibration, but will need further studies and methods to remove fake photons at the trigger level.

Acknowledgements

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I would also like to thank everyone else, here or elsewhere, who have helped me or supported me.

Acronyms & Abbreviations

ATLAS – A Large Toroidal LHC ApparatuS
HLT – High Level Trigger
L1 – Level 1 Trigger
LHC – Large Hadron Collider
MACHO – Massive Compact Halo Object
MOND – Modified Newtonian Dynamics
SM – Standard Model
TLA – Trigger-Level Analysis
WIMP – Weakly Interacting Massive Particle

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1 Introduction

Dark matter makes up most of the matter in the universe. Despite this, its presence is only inferred through the gravitational interaction of dark matter with standard matter. [1] It is not described by the Standard Model of particle physics (SM), and what it is made of is not known, since it only seems to interact gravitationally, but there are models that describe possible candidates for dark matter [2]. One hypothetical description of dark matter is that of Weakly Interacting Massive Particles (WIMPs). These are massive particles, thus interacting gravitationally, and can interact with standard matter, though only very weakly. These particles could be detected, given that they are present in the universe. The amount of dark matter in the universe is called relic density [2].

There are searches for dark matter looking for the possible interaction between it and ordinary matter. At the Large Hadron Collider (LHC) these searches involve the production of dark matter or the particles that could mediate the interaction between them. Depending on the model of dark matter considered, there are different signatures that sought after, such as the decay of the mediator particle or the absence of energy in an event from particles that were produced but not detected. As the LHC produces a large amount of data certain strategies can be employed in order to aid in the search for specific models by choosing which data is analysed.

The Trigger Level Analysis (TLA) is a method developed to be able to analyse the large amounts of data produced in events at the LHC and recorded in the ATLAS (A Large Toroidal LHC ApparatuS) detector. Not all data produced by the LHC can be recorded in full. To reduce the amount of data recorded, the experiments use a trigger system to only store events that fulfill certain criteria, otherwise the events are discarded. Typical criteria are the energy of the detected particles, and so even signal events could be discarded if they are of too low energy. An example of signal events that are normally discarded is that of decays from particles with a mass below 1 TeV and decaying into two quarks that hadronize into sprays of collimated particles (jets). As the LHC is a hadron collider there is a large number of these events, and so many of them are discarded. To overcome this problem, the TLA strategy records only partial events, prior to the event being accepted or discarded by the trigger. With this method, a larger number of events, signal or background, can be recorded so that searches for processes with events that are typically discarded can be carried out. These partial events only contains a subset of the information, so it is important to check whether this information is sufficient to obtain a performance for the physics objects that is comparable to that of full events. The aim of this work is to investigate whether searches for dark matter mediators can be done with final states of photons, in addition to the existing search with jet final states [3].

In the next subsection the motivation for the project work will be presented. The following two sections are dedicated to the necessary background for the work. This gives a brief background to particle physics and dark matter, plus highlighting some current searches for dark matter and explaining the model considered here. Then the experimental tools necessary for the analysis are presented. Following that the plots used for the analysis are shown together with discussion. Lastly, a conclusion with hints at possible future studies.

1.1 Motivation for the work in this thesis

In this work the dark matter model considered is that of an unknown mediator boson Z', which is a copy of the SM Z boson but more massive, which would mediate an interaction between DM and ordinary matter [4]. This model assumes that the Z' boson couples to both SM and DM particles. The dark matter particles themselves are similarly of a particular model. Here we consider the case of light dark matter, where the dark matter mass is of the order of 10 GeV.

In order to be related to dark matter, models should be able to produce the correct WIMP relic abundance. In order for the light dark matter mentioned above to fulfill this criterion, it requires that the dark matter mediator should similarly be light, on the order of 100 GeV [4]. A mediator of this mass could conceivably be produced at the LHC, as it is assumed to couple to SM particles. We assume this mediator to be leptophobic, meaning that its coupling to leptons is very small, relative to quarks. This is assumed, as a mediator with a larger coupling to leptons would be likely to have been seen at the Large Electron-Positron Collider [4].

This work considers a light dark matter mediator decaying to two jets, produced in association with a photon. We plan to search for this final state using a TLA. This final state is advantageous with respect to jet-based final states because the backgrounds are lower and therefore we can reach lower mediator masses.

A TLA including both jets and photons could potentially provide further constrains on the interactions of this model of mediator. This is due to the fact that a light mediator particle produced as a resonance at the LHC, if it decays into two quarks, will produce two jets of relatively low energy. To effectively be able to detect jets, at least one of them has to have a high enough energy to pass the trigger selection of roughly 400 GeV: this is unlikely for mediators of mass around 100 GeV.

Instead of using the jet to trigger the event, we can use associated photons produced as initial state radiation alongside the resonance [5]. This is a less frequent process than the production of the mediator only, but it has the advantage of allowing to reach lower mediator masses. It is also advantageous to use the TLA technique so that the threshold for recording photons can be lowered further with respect to the case in which the full events are recorded.

2 Theoretical Background

This section goes through some of the necessary particle physics background for the work in this thesis. First, the basics of the Standard Model of particle physics are explained. Following this dark matter and why it is thought to exist. Then a brief overview of some of the current experimental searches for dark matter is given. Lastly, the model considered in this work.

2.1 Standard Model of Particle Physics

The fundamental components of matter and their interactions are described by the Standard Model of particle physics. The SM that describes all known elementary particles and three of the four fundamental forces describing their interactions [6].

The elementary particles are split into two broad categories, fermions and bosons. Some of the elementary fermions are what make up matter. Fermions have half integer spin.

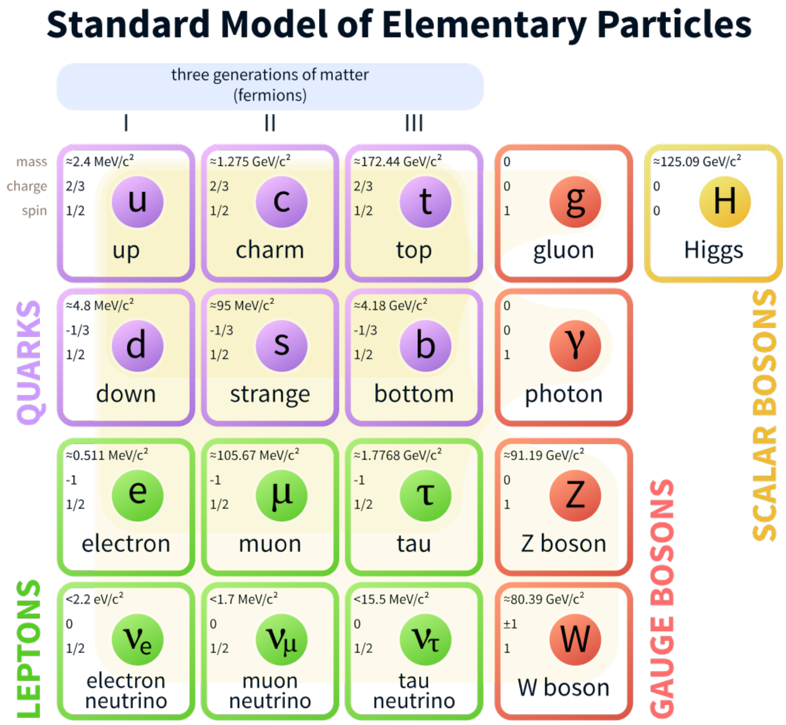

Figure 1: The elementary particles in the standard model, showing the two different fermions and their three generations, the four mediator bosons, and the Higgs boson [7].

They are further split into two groups, quarks and leptons. Similarly, bosons, which have integer spin, are split into gauge bosons and a scalar boson. The gauge bosons have spin 1, they are the particles which mediate the interactions between the other particles. There is one scalar boson, the Higgs boson, with spin 0, which does not mediate any interaction but is responsible for giving mass to other particles in the SM [6]. These particles are shown in Figure 1

Interactions between particles occurs via the exchange of one of the gauge bosons, depending on the interaction. The strong force is an interaction between color charged particles, mediated by the massless gluons. Quarks are the only fermions with color charge, and so the only ones that couple to gluons. The strong force has a range of around 0.8 fm. The electromagnetic force is mediated by massless photons, and only couples to electrically charged particles, meaning quarks and the charged leptons. Due to the massless photon, the electromagnetic force has infinite range. While the strong force similarly is mediated by a massless boson, it does not have infinite range, due to a property of the strong force called color confinement, stating that no color charged object can exist in isolation. The final force described by the standard model is the weak force. Unlike the other two forces, the weak force is mediated by massive bosons, the $W^{\pm}$ and Z, which couple to all elementary fermions. Due to the massive force carriers the weak force has limited range [6].

While the SM successfully explains many phenomena observed in particle, there are still a few that are either not succesfully explained, or not at all. These typcially require some kind of extension of the current SM. Dark matter is one of these phenomena.

2.2 Dark Matter

The existence of dark matter is supported by large amounts of evidence in its favor [2]. Originally, the existence of unseen matter was inferred from the observation of the Coma Cluster in 1933. Based on the number of visible galaxies in the cluster and the motion of these galaxies, there ought to be more mass than was visible in the cluster. Thus there was some unseen matter there. Following that, in the 1970s, the measurements of galactic rotation curves provided more evidence for the presence of unseen matter. Measurements of the rotational velocity of galaxies around their centers showed that beyond a certain point away from the galactic center the velocity remained roughly constant. This was contrary to theoretical predictions, which said that the rotational velocity would decrease the further away from the center a star was.

Dark matter is not the only possibility in explaining these astrophysical observations. Another major possibility is that of modifying the description of the gravitational force such that it is able to explain observations. This is called Modified Newtonian Dynamics (MOND). According to MOND, Newtonian gravity is insufficient in explaining gravitational interactions when the acceleration due to gravity becomes small. This value for the acceleration is $a_0 = 10^{-12}\,\mathrm{m/s^2}$. At this level MOND successfully predicts the rotational velocity of galaxies, but is unable to explain the behavior of galaxy clusters. Thus MOND does not have the same explanatory power as the hypothesized dark matter. Extensions to MOND exists, though despite this, the shortcomings of the modifications are not yet sufficient to explain the previously mentioned anomalous observations [2].

The nature of dark matter is unknown, and there are many possibilities. One is that dark matter is made of astrophysical objects, named Massive Compact Halo Objects (MACHO). These could be for example isolated black holes or brown dwarves, stars without enough material to burn hydrogen, which do not emit light [2]. They would thus be classified as dark, since they would not be accounted for when looking at visible galactic matter. Since these astrophysical objects, other than black holes, are made up of ordinary matter they would be classified as baryonic dark matter. Gravitational lensing experiments meant to observe gravitational lensing, light bending in the gravitational field of a massive object, from the presence of MACHOs have failed to account for the required dark matter content of the Milky Way [8].

If dark matter cannot be made up of baryonic matter, then it would seemingly need to be made up of non-baryonic matter. One primary candidate of this is in the form of Weakly Interacting Massive Particles. These are dark matter particles that interact only gravitationally and through a force with a coupling on the order of the weak force. If the interaction was of a significantly different strength, and these particles were created in the early universe, there would either be too many or too few of them in universe today to explain the astrophysical observations, due to annihilation of WIMPs. This remaining dark matter in the universe is called the relic abundance [2, 9]. Additionally, WIMPs cannot interact through the electromagnetic force, as they would then couple to photons and would thus be visible. This weakly interacting particle would be a good candidate to interact with ordinary matter [2].

2.3 Dark Matter Searches

The detection of dark matter interacting with ordinary matter can be done in three main ways. If dark matter particles interact with SM particles, these interactions might be observed in detectors made of ordinary matter. This is what direct detection experiments,

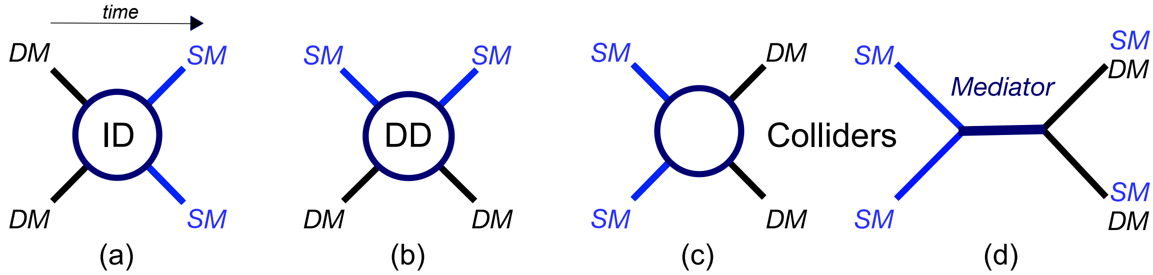

Figure 2: The interactions between dark matter and SM matter. a) shows the interaction sought after in indirect detection experiments, where two WIMPs annihilate to form SM particles. b) shows the direct interaction between a WIMP and a SM particle. c) & d) show the two collider possibilities for dark matter. In c) two SM particles annihilate to create a final state with two WIMPs that do not get detected, leading to missing energy in the event. In d) two SM particles create a mediator particle which can couple to both SM partcles and WIMPs [12].

like the XENON experiment [10], are aiming to do by. Large amounts of xenon are stored in an underground laboratory. If dark matter can interact with the xenon, it would scintillate or ionize, and be detected in the detector. An alternative to directly detecting it is to detect the result of an interaction between two WIMPs resulting in an interaction in space or in the sun. In the example of the IceCube neutrino observatory [11], the WIMPs that interact gravitationally are attracted to the sun when passing through the solar system at correct trajectories and velocities. If large quantities of WIMPs gather in the sun, they might annihilate, and some of the possible SM products of the annihilations (neutrinos) could be detected on earth. The IceCube neutrino observatory is looking for neutrinos with energies not predicted to occur during solar fusion. The third possibility, and the one relevant to this thesis, is the production of dark matter at the LHC, or another collider. If WIMPs couple to ordinary matter, it is possible that WIMPs, or mediator particles, could be produced at the LHC from proton-proton collisions, given that they are of the correct mass [4].

2.4 New physics models and signature considered for this thesis

In collider searches for dark matter two of the dark matter signatures that are looked for are shown in Figure 3. One of these is the search for missing transverse energy in an event. This occurs when two dark matter particles are produced, either in some unknown interaction or from the decay of a mediator resonance. If these particles are not detected there will be energy missing in the event, as the total energy of the event ought to be conserved. The signature for this event is a single SM object, a jet or photon, and missing energy [14].

The other dark matter signature is the production of a mediator resonance and the decay into quarks, which will lead to a dijet event, an event with two jets. The signature considered in this thesis is based on the model described in Section 1.1. On top of the two jets from the resonance decay in Figure 3, an additional final state photon is required in the event, in order to effectively trigger on the event. The signature is thus a dijet event with a photon.

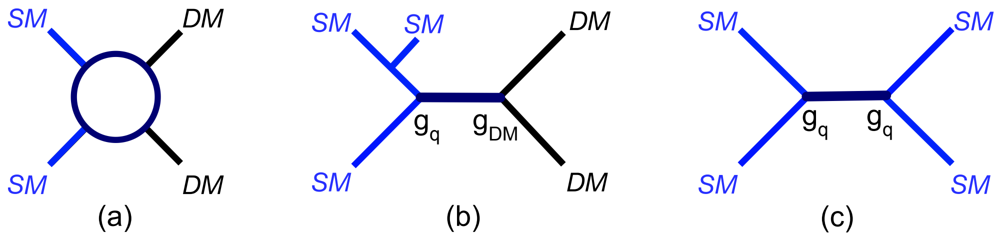

Figure 3: Three possible signature from a dark matter event in a collider. a) shows the production and escape of two WIMPs, leading to a missing energy signature. b) shows the decay of resonance mediator into two WIMPs, together with a SM object in the final state, leading to a jet or photon plus missing energy signature. c) shows the decay of the resonance into two quarks, leading to a dijet siganture [13].

3 Experimental Tools

This section aims to explain the experimental tools used at the ATLAS experiment relevant to this work and the associated physics. An overview of the LHC and the ATLAS detector is given. The kinematic variables used in the analysis are presented. Jets and photons and how they are detected is discussed. Finally the ATLAS trigger system and Trigger Level Analysis are presented.

3.1 The LHC and the ATLAS Experiment

The LHC is a circular collider typically using either protons or lead in the collisions. Here only the protons are considered. The protons are accelerated in bunches to an energy of 6.5 TeV in opposite direction so that when they collide the total center of mass energy of the collision is 13 TeV. Collisions occur at certain points along the ring, where the experiments are situated [15].

The ATLAS experiment at the LHC is one of the major experiments at the site. It acts as a multipurpose detector. For particle detection it uses a cylindrical detector composed of multiple layers. These are, in order of distance from the beam pipe, the Inner Detector, Calorimeter, and Muon Spectrometer. In addition there is a system of magnets throughout the detector used to bend particle trajectories [16]. Figure 4 shows a cross section of the ATLAS detector.

The Inner Detector is used to track particles produced in collisions at the beam crossing. The magnetic field in the detector bends the trajectory of charged particles, and allows for the reconstruction of where the particle originated from, either directly from the collision or from the decay of a produced particle [3].

Two types of calorimeters are used, depending on the particle type intended to interact with them. This is because they are meant to stop the particle in the detector, in order to be able to measure their energy. When a produced particle enters the detector it interacts with the material to create many more particles, which are detected. The electromagnetic calorimeter detects particles using the electromagnetic interaction, such as photons or electrons. The hadronic calorimeter detects strongly interacting particles, and thus also the jets that we describe below [3] .

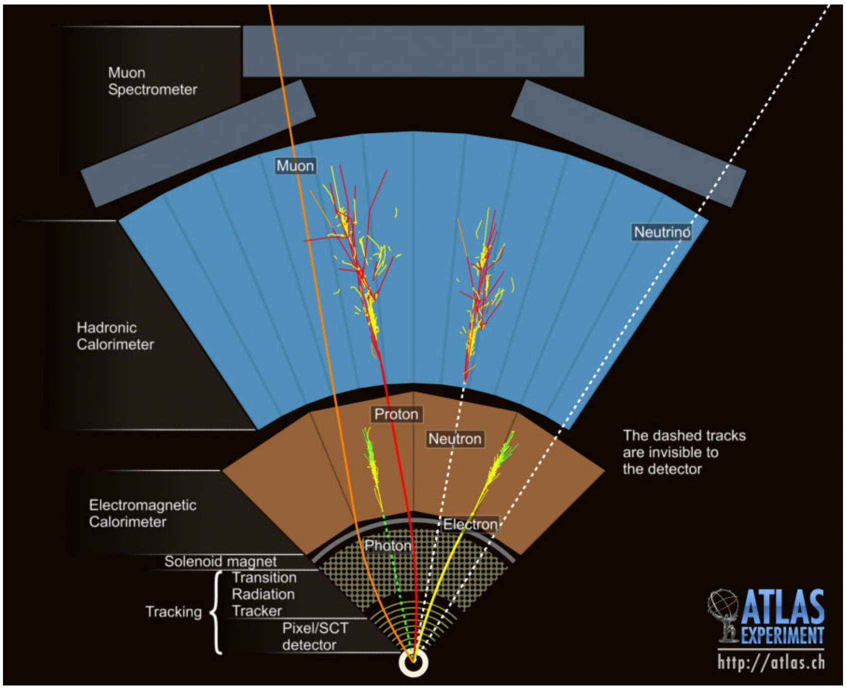

Figure 4: Schematic showing the cross section of the ATLAS detector, including the different calorimeters, the Muon Spectrometer, the solenoid magnet, and the tracking system. Different particles and their interaction with the different components of the detector are shown [17].

The Muon Spectrometer is a separate part of the detector designed specifically to detect muons. It is outside the other components of the detector, as the they are not designed to detect muons, which are like electrons with a greater mass. With this design the muons are likely to pass through the other components, and so they can be detected on their own in one of the muon chambers in the outer parts of he detector [3].

3.2 Particle kinematics in the ATLAS detector

The kinematic variables considered in the analysis for this thesis are the transverse momentum p_t, the azimuthal angle ϕ, and the pseudorapidity η. The transverse momentum is the component of the momentum of a particle that is perpendicular to the beam axis. As the transverse momentum is perpendicular to the direction of the beam, it must always add up to 0 in an event, as the incoming beam has no momentum in the transverse direction. Since there is no initial p_t the detected magnitude of it must come from the interaction of particles in the beam, rather than from the beam itself, which might be the case for non-transverse momentum [6].

The angle ϕ is a measure of the angular distribution of particles in the transverse plane, that is, the plane orthogonal to the beam direction. The pseudorapidity η is similarly a measure of the angle of a detected particle. It is defined based on the polar angle θ, which is the angle between a particles momentum and the beam axis. It is defined as

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right). \tag{1}$$

From the definition it is clear that the value of η is between zero and positive ∞. $\eta = 0$ if $\theta = 90\ ^\circ$, and $\eta = \infty$ if $\theta = 0$. A high pseudorapidity thus means that a particle is

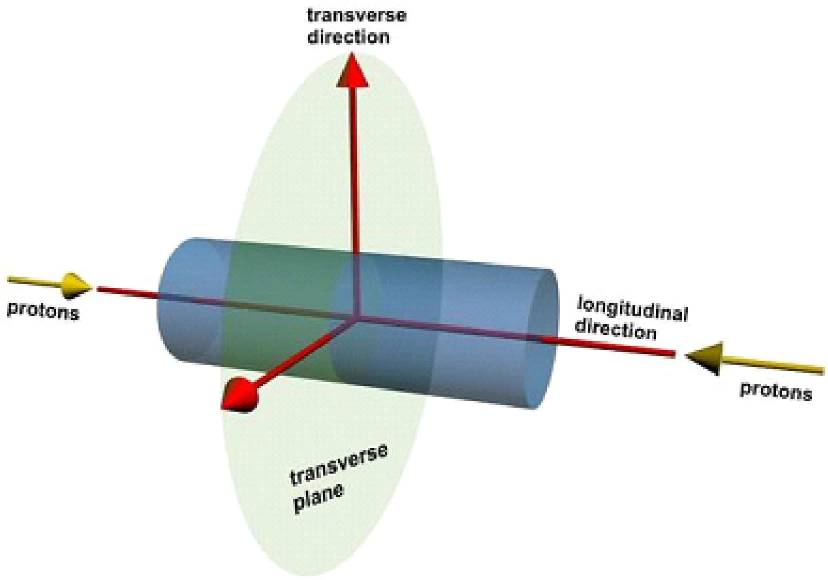

Figure 5: The transverse plane in the ATLAS detector, showing its position relative to the beam axis. The plane is orthogonal to the directions of motion of the incoming protons [18].

moving roughly along the beam line. ϕ and η can further be used to define the angular separation of two objects in a detector. This is given as

$$\Delta R = \sqrt{((\Delta\eta)^2 - (\Delta\phi)^2)} \tag{2}$$

where ΔR is the angular separation between the two objects, and $\Delta\eta$ and $\Delta\phi$ are the differences in the respective variables between the two events. The angular separation is here used to match two events together based on whether the angular separation is smaller than some arbitrary value.

3.3 Jets in ATLAS

In particle production at the LHC large amounts of strong interactions occur, as the LHC is a hadron collider. This produces large amounts of quarks, as they interact strongly, and thus the final state of many interactions consist of hadrons. A group of final state particles moving in the same direction is known as a jet. Jets are a result of the color confinement property of the strong force, which requires that no color charged object can exist in isolation, rather only composite objects where the constituent color charges cancel out, or colorless particles, can exist in isolation. Thus when a high energy quark, or gluon, is produced in a collision it cannot remain isolated, and so color charged objects are pair produced in a process called "hadronization", creating large numbers of hadrons. When a jet enters the either of the calorimeters the constituents of the jet interact with the material in the calorimeter to produce many more particles in the detector. This is known as a hadronic shower. The energy of this shower is used to detect jets [6].

Identifying jets in the ATLAS experiment is done by using so-called jet algorithms. These are algorithms in the detector that classify a hadronic shower as a jet based on where the particles are detected in the calorimeter. It is important that these algorithms are able to correctly classify and identify sets of jets as one or multiple jets even in the case where additional lower energy particles are emitted by the hadrons [3, 19]. Two examples of algorithms are the k_t and anti-k_t algorithms. These algorithms determine whether multiple pairs of objects belong to a jet by considering the transverse momenta of the two objects and their relative angular separation given by Equation 2. This is compared to either the transverse momentum or its inverse. Depending on which variable is greater the two objects are either put together into one object and compared to another particle or declared to be a jet. If the object is declared a jet the algorithm continues in the same way until all particles in the event considered to belong to a jet have been analysed [19]. The detected energy of the jet is not necessarily the true energy of the jet, and so the jet must be calibrated at reconstruction in order to come closer to the true energy.

3.4 Photons in ATLAS

Identifying a detected object as a photon is different from identifying a jet. Jets consist of many mostly hadronic objects within a region of the detector. If this is detected the jet algorithms in the previous section are used to reconstruct the detected object as a jet [3]. Photons differ here, as they interact electromagnetically, and are thus detected in the electromagnetic calorimeter, rather than the hadronic one. On top of that, photons are single objects and will thus give of smaller signatures in the detector and will be easier to isolate and detect. An issue in reconstructing photons is in the identification of the photons and their source. Since there is a large hadronic background at the LHC it is inevitable that large numbers of photons are produced in association with hadrons in jets. This gives a significant photon background. The background can be reduced by accounting for the fact that photons produced from a jet will also be accompanied with large amounts of energy in the hadron calorimeter in the same region. Thus, if these two are detected within some angular separation, then the photon background can be reduced [20].

3.5 Triggers in ATLAS

A trigger system is used by particle physics experiments to select only certain events for further analysis. This is needed due to large amount of data produced in every collision. As all events cannot be stored, only those deemed interesting are selected. The decision is typically done based on the energy of the object detected, the lower the energy the fewer events are stored [3]. There are a large number of low energy events that are discarded due to the fact that at low energies the coupling of the strong interaction increases. In a hadron collider there will thus be a lot of events at low energy, as strong interaction are more likely to occur[6].

The ATLAS trigger system consists of two levels, to enable fast decision making at the first level and to have more time to analyse a lower rate of events and select a fraction of them for storage at the second level. The first level, called Level 1 (L1), selects events that have a significant higher transverse energies in groups of calorimeter cells relative to surrounding cells. At this level the objects are treated depending on whether the objects are detected in the electromagnetic or the hadronic calorimeter. In the electromagnetic calorimeter most objects are likely to be either photons, electrons, or tau leptons. Since these are single objects, rather than clustered like jets, the L1 trigger analyses high transverse energy events that are isolated in the calorimeter. Furthermore, the object should not leave energy in the hadronic calorimeter in the case of electrons or photons, or some presence in the hadron calorimeter from tau decay [21]. When searching for jets an algorithm that is simpler than the proper k_t and anti-k_t algorithms is used. This algorithm looks at so called trigger towers, which are stacks of calorimeter cells in a certain area of the detector. It uses groups of trigger towers from both of the calorimeters, and compares the transverse energy in these towers to some threshold to define regions of interest that are sent to the higher level [3, 21].

The High-Level Trigger (HLT) takes the events that passes the L1 trigger selection and analyses them in more depth, using more information from the calorimeter and tracking detectors. Similar to the L1 trigger it treats electromagnetic and hadronic objects differently. For photons the L1 data is used in the first step of the reconstruction, while for electrons tracking information is also available at a later stage at the HLT. The reconstruction then uses algorithms similar to the offline reconstruction with the full detector granularity of the calorimeter, instead of the more coarse groups of calorimeter cells used at L1 [22]. Jets are similarly reconstructed using the same anti-k_t algorithm as for offline jets. Here the all relevant calorimeter cells are used in full, and they are clustered together based on their energies. These clusters are put together into jets using the algorithm. Further criteria are used together with the found HLT jets to select the events that are stored with all available data [22, 23].

Instead of using the full reconstructed data for only events that pass the HLT selection, the Trigger Level Analysis strategy can be used. As the HLT requires certain criteria to be fulfilled in order for an event to be stored, it is inevitable that a large number of events are discarded. In a hadron collider there is a very large background of hadronic events, jets, and so only those with a high enough transverse energy are typically stored, as they are deemed the most interesting ones. The HLT only outputs events at a rate of 1 kHz, and the more events there are, the more low energy ones are discarded. TLA overcomes this by only recording part of the event in order to store a larger quantity of events instead of fewer high information events. One limitation due to less information stored is the fact that photon and electron candidates have no tracking information stored [24].

In the TLA data format, jets are chosen based on the energy recorded at L1 only. The jet four momentum and variables needed to characterize jets at the HLT are stored, but beyond that no tracking or calorimeter data is saved. This leads to significantly smaller event size, and thus the rate of events stored for this kind of event is up to 3 kHz. The jets stored here are comparable in properties to those reconstructed offline [24].

The aim of this thesis is to verify that the offline and trigger jets have a similar performance, and investigate the performance of trigger photons for the first time.

4 Results & Analysis

This section presents the results in the form of the kinematics of the jets and the photons, and both of their responses. The displayed graphs are the kinematics of both the matched and unmatched objects, in order to compare the jets and photons at the trigger-level. The responses are shown to be able to compare how TLA with photons would compare to jets.

4.1 Data Analysis

The analysis in this thesis was done using the ROOT framework [25] and data from the ATLAS detector taken in 2017, consisting of collections of jets and photons. The data contains the kinematic variables described above for both jets and photons. Jets and photons are separated into two collections, one where the objects are reconstructed at the trigger level with reduced information, and one where they are reconstructed using the full detector information. Jets have been reconstructed using the anti-k_t algorithm. Each collection has many "branches" for each of the variables recorded. Each of the branches is filled with events containing values of the corresponding variable for each of the jets or photons in the event. This analysis considered, other than the kinematic variables, the response and resolution of the jets and photons. These are found by taking the ratio of the transverse momentum of the reconstructed trigger-level object and the fully reconstructed object, given below.

$$response = \frac{p_{T,trigger}}{p_{T,offline}} \tag{3}$$

The mean response is the mean of this curve, while the resolution is related to the standard deviation and mean of the distribution. The response is thus a measure of how detected objects change from the trigger level to full reconstruction.

As there are different events reconstructed at the trigger and offline level, and each event might contain different numbers of photons or jets on the two levels, the two collections are compared on an event-by-event basis including objects that are present in both. Objects in the two collections are matched based on the angular separation of the objects, given by Equation 2. If two photons in the same event, one on the trigger level and the other reconstructed had an angular separation of $\Delta R < 0.1$, then they were matched and taken to be the same photon. For the jets, the separation used was $\Delta R < 0.4$. This difference comes from the fact that photons are single objects, thus have a smaller spatial extension in the calorimeter compared to jets. Only if two objects were matched they were used for plotting the response.

4.2 Jet Kinematics

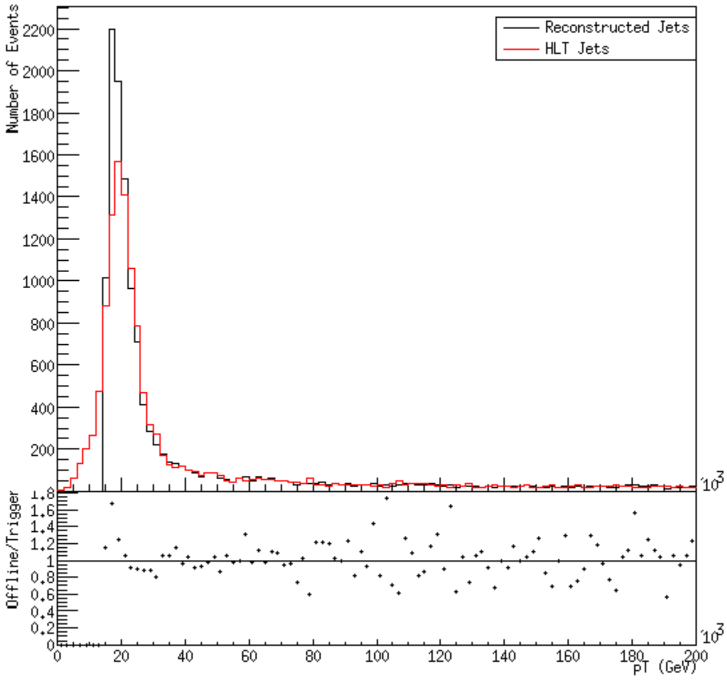

Figure 6: Distribution of the transverse momentum of the collection of jets, showing both the reconstructed jets and the jets at trigger level, but only of those jets that have been matched. The ratios were obtained by dividing the two distributions by each other after having generated the histograms, rather than dividing individual entries.

The histogram in Figure 6 shows the distribution of the transverse momentum of the jets that have been matched according to the criteria above. In the figure there is a clear point at 15 GeV that shows the p_T cut used in the reconstruction, while the trigger jets have no such cut.

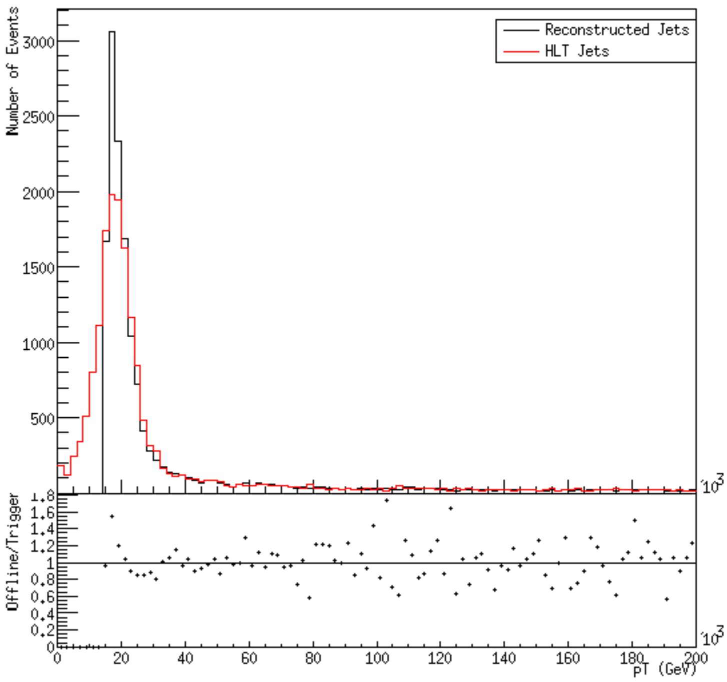

Figure 7: Distribution of transverse momentum of all jets in the collection. The ratio plot is the ratio of the two histograms showing the distirbutions.

Figure 7 shows the same distribution as in Figure 6, but for all jets rather than for only those that have been matched. There is some difference in the two distributions, as the offline peak is broader without matching and the trigger jets show a bump at 0 GeV. This is most likely due to jets that are formed from proton-proton collisions that are not from the one of interest and have received a large corrrection factor. Without excluding these events when creating the histograms they are all then assigned to the first bin at 0 p_T.

4.3 Photon kinematics

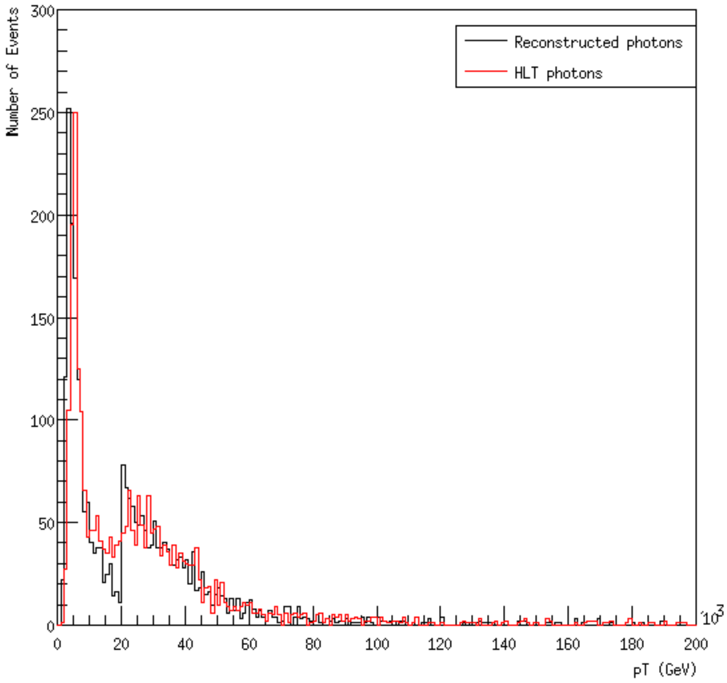

Figure 8: Transverse momentum distribution of the matched photons showing both the offline and trigger photons.

Figure 8 shows the same momentum distribution as Figure 6, but for the matched photons. The two distributions are similar, with both of them having a cut in the plot at 5 GeV. For the generation of this plot a cut on which events were used in the matching was used, in order to decrease the number of events plotted. The resaon for this will be discussed later. The cut consisted of a requirement of there being at least one 20 GeV offline photon in the event for it to be considered for matching.

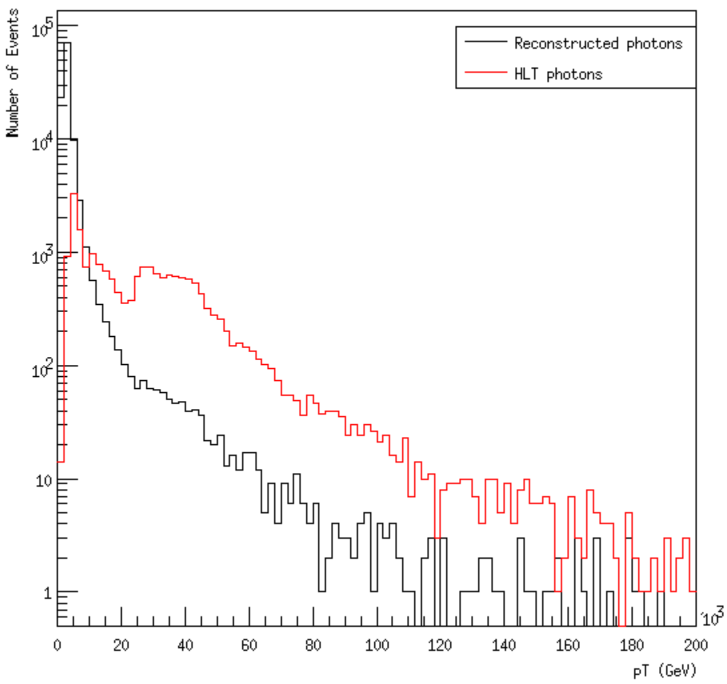

Figure 9: Transverse momentum distribution of all the photons, showing both the reconstructed photons and the trigger photons.

Figure 9 shows the momentum of all the photons, regardless of whether they passed the above mentioned cut or not, and without any matching. A logarithmic scale is used due to the large number of offline events. The distribution shows that there are quite a large number of very low p_T events among the reconstructed photons. This distribution includes an order of magnitude more events than that of only the matched photons, and we will discuss hypotheses for this observation later.

Neither of the plots in this subsection include ratios, due to the large number of offline events.

4.4 Response

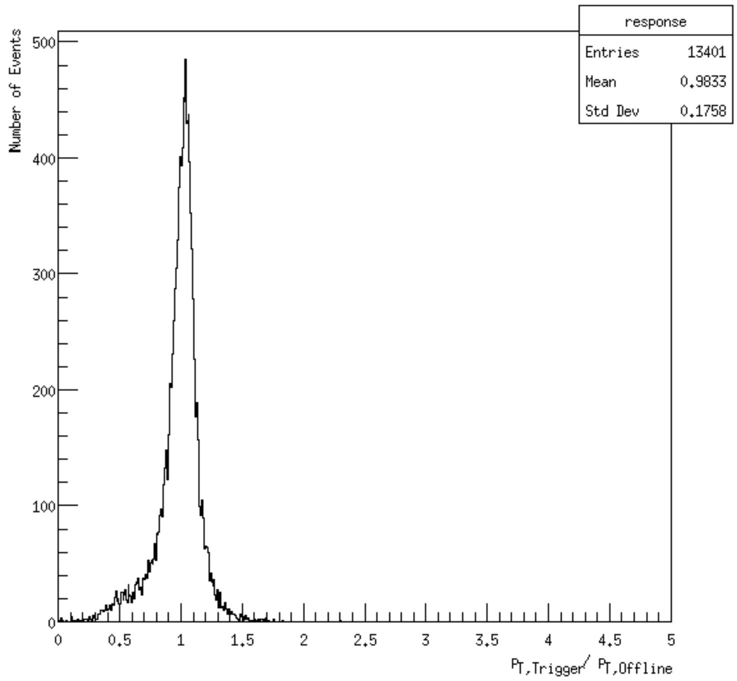

Figure 10: Jet response histogram showing the transverse momentum of the trigger jets divided by the offline jets.

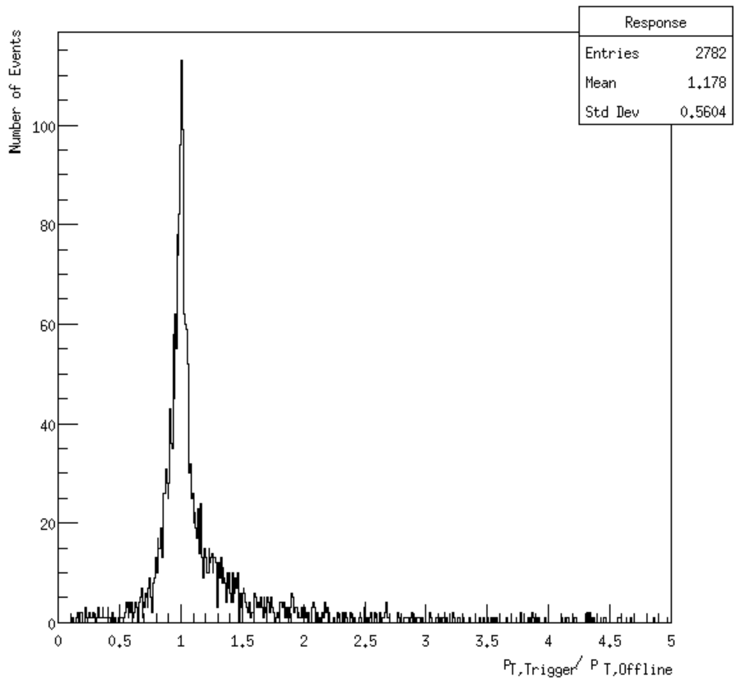

Figure 11: Photon response showing the transverse momentum of the trigger photons divided by the offline photons.

Figures 10 and 11 show the responses of the two collections. Comparing the two plots shows that both responses have means around 1. The photon mean is slightly smaller than 1, while the jet mean is in the opposite direction. The photon response also has a significant tail beyond 1 which does not show up in the jet response. This likely comes from the large umber of low p_T photons among the offline ones.

Of note in the analysis of the photons is that Figure 9 includes a much larger number of events than the matched photons, and in particular the number offline photons is significantly larger than trigger photons. This is the reason for why the criterion on the photons of requiring at least one offline photon with $p_T > 20$ GeV in an event was used. Without this criterion there are some events which include a large number of low p_T offline photons, but very few or no high p_T ones. As there is a large number of offline photons it is thus likely that one of them gets matched with a trigger one, despite having momentum that is an order of magnitude or two smaller. This creates a longer tail in the response at values greater than 1. The reason for the absence of high p_T photons in events at the trigger level could be due to the absence of any tracking information, and so a high p_T electron or jet could be mistaken for a photon.

Since there is no tracking information available at the trigger level objects detected in the electromagnetic calorimeter that look like photons are not necessarily photons, or alternatively photons radiated from one of the other final state articles in the event. This leads to the possibility of fake photons, where a jet or an electron look like a photon on the trigger level and is thus mistaken for a photon. If an electron radiates a photon in the detector it is possible that the electron is detected as a photon on the trigger level. The photon from the electron could be matched with the electron rather than itself after reconstruction. If the electron has a high energy it will contain most of the energy even after radiating a photon, and thus the response is big, since the trigger electron has more energy than the offline photon. This could explain some of the right tail in Figure 11.

The same problem does not exist for jets. There are a large number of jets produced in any given event, since the colliding particles are hadrons. Even though photons and electrons would be reconstructed as jets, their number is insignificant compared to the number of jets from the dominant strong interaction processes.

5 Conclusion & Outlook

The aim of this work was to investigate the performance of jets on the trigger level and use this to make a basic comparison to the performance of photons on trigger level.

Trigger-Level Analysis is a strategy used for analysing events that would otherwise not be recorded for offline analysis, typically due to the low energy of the event. Instead of using the full information of the event TLA uses only a limited amount to be able to store more events than are stored for offline reconstruction. This allows for lower energy processes, such as the decay of the mediator resonance used here, to be analysed when they otherwise would have been discarded,

As a TLA with photons has not been used to the extent that it has with jets, it is an investigation into a possible analysis technique for specific dark matter models. Using photons might be of assistance in mediator mass ranges where the jets from the decaying resonance are not sufficiently energetic to pass the jet TLA criteria. By requiring a photon in the final state these events can pass the trigger criteria with lower energy jets, because of the reduced rates of SM processes including a photon. With a TLA using photons a larger number of events can be analysed, provided that trigger photons do not deviate significantly from those reconstructed offline.

Looking at the jet results it can be seen that there is no large difference between the distributions, as most of the jets were matched. Comparing this to the photons on both levels, we see that there is a large number of supposed photons at low energies. Since there are so many objects that look like photons on the trigger level, mainly electrons and low energy jets, these must be accounted for when performing a TLA with photons. In this work a cut on the offline photons was used in order to remove a large number of offline events with only low energy objects. This requirement of a high energy photon in an offline event when matching events significantly decreases the number of offline objects, but does nothing to identify the type of object and does not necessarily make it more likely that the trigger photons is not fake.

Performing the matching after the photons cut in order to generate a response gives a result that has a larger mean and standard deviation than the jets. The photons are likely to have a broader distribution than the jets, as there are more potential objects that could be photons, whereas there are a large number of jets, but they are not as easily faked as the photons. As both responses are close to 1, it indicates that there is very little change in the momentum from the HLT to reconstruction. Since this was done without any calibration of either of the two objects it means that they both have similar performances at HLT and reconstruction. Specifically for the photons this means that they could potentially be used with TLA, as they display similar performance without calibration. Whether TLA with photons actually is viable requires further investigation.

Further analysis could be conducted by looking at the potential fakes in order to able to further distinguish between the fake photons and actual photons. This is necessary in order to be able to use TLA with photons, as any fake events affect the photon performance. If the photon performance is good enough for TLA, then further studies could look into what kind of cuts are appropriate for photons and jets with this method, before proper studies or searches could be done. Beyond that would be to analyse the photons and jets together to investigate whether this method could be useful in the search for mediator resonances.

Currently there is no tracking information available at HLT, and so this cannot be used for TLA. The Fast TracKer is a hardware tracker that will be able to supply tracking information to the HLT when implemented. This will be beneficial to TLA with photons and further investigations, as it allows for better distinguishing between photons and electrons or jets faking photons [26].

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